CROSSTEX – Wave Breaking, Boundary Layer Processes, the Resulting Sediment Transport and Beach Profile Evolution

Tian-Jian Hsu
Woods Hole Oceanographic Institution, MS#11, Woods Hole, MA 02543
phone: (508) 289-2654 fax: (508) 457-2194 email: thsu@whoi.edu

John H. Trowbridge
Woods Hole Oceanographic Institution, MS#12, Woods Hole, MA 02543
phone: (508) 289-2296 fax: (508) 457-2194 email: jtrowbridge@whoi.edu

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LONG-TERM GOALS

To develop and test with laboratory and field data a robust modeling framework that predicts hydrodynamics and the fate of terrestrial and marine sediment in the heterogeneous environment.

OBJECTIVES

- Develop detailed numerical models for surfzone hydrodyanmics and bottom sediment transport processes. Validate these models using data measured in CROSSTEX.
- Develop simplified phase-resolving formulations for concentrated sediment transport, suspended load transport and its near-bed boundary conditions under breaking waves.
- Calibrate the simplified formulations for predicting local sediment transport rate and beach profile evolution under breaking waves using measured data.

APPROACH

Several numerical models are extended to simulate data measured in CROSSTEX. A two-dimensional phase/depth-resolving wave hydrodynamic model (COBRAS) solving Reynolds-Averaged Navier-Stokes equation (RANS with nonlinear eddy viscosity k-ε closure) for fluid flow and volume of fluid (VOF) method for free-surface tracking (Lin & Liu 1998; Hsu, Liu & Sakakiyama 2002) is adopted as a numerical wave tank to simulate the wave shoaling, breaking processes in the physical experiment. A detailed two-phase sheet flow model (Hsu, Jenkins & Liu 2004), modified to be driven by measured near-bed flow velocities and turbulence, is adopted to model both the concentrated to dilute sediment transport processes. In the physical experiment, sediment transport measured in the dilute region (volume concentration <5%) will be used to validate the two-phase model. On the other hand, numerical results for concentrated sediment dynamics provided by the two-phase model can bridge the missing information between the bed and the dilute region, which is difficult to measure in the physical experiment. A dilute model for suspended load transport, reduced from the complete two-phase model is coupled with COBRAS to simulate non-local transport dominated by advection under shoaling broken waves (Hsu & Liu, 2004). The two-phase model results along with the measured data will be analyzed to develop simplified formulation for transport rate in the concentrated region as well as parameterizations for near-bed boundary condition (e.g., reference concentration) used by dilute suspended load model under breaking waves.

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WORK COMPLETED

The major physical experiments of CROSSTEX was just completed in September 2005. For year 2005, most of our research efforts were devoted to numerical model development. The dilute sediment transport formulation has been successfully coupled with the wave model COBRAS and tested with available laboratory experiments (Hsu & Liu 2004; Amoudry, Hsu & Liu 2005). The coupled model is ready for direct model-data comparison of suspended sediment transport under waves measured in CROSSTEX. The two-phase sheet flow model of Hsu et al (2004) was originally developed for massive particles (diameter > 1mm). Major effort has been made to extend the model for transport of medium to coarse sand (e.g., diameter~0.2mm) usually encountered in sandy beach (see figure 2). Additionally, the two-phase model was modified to take (arbitrary) measured near-bed velocity and turbulence time series as forcing (Hsu & Raubenheimer, accepted), which is critical when conducting model-data comparison with CROSSTEX data in the near future. In the beginning of this year before the physical experiment of CORSSTEX, the two-phase model is utilized as a tool, driven by measured near-bed flow velocity during CROSSTEX pilot experiment for fixed concrete bed (Scott, Maddux, Cox & Long 2005) to estimate the magnitude of bottom stress that would be achieved when the real sand bed is implemented (figure 1). Prior research efforts for the RANS wave model (COBRAS) focus on testing with small-scale laboratory experiments (mostly monochromatic wave). This year, the wave model has been tested with field measured wave hydrodynamic (Raubenheimer 2002) in the surf zone at Torry Pine beach, CA (see figure 3 for details).

RESULTS

Two-phase sheet flow model:

Through extensive physical analyses and model-data comparisons, the two-phase sheet flow model is now capable of simulating sand transport of a range of sizes. The dominate transport mechanisms for medium to fine sand can be significantly different from that of coarse sand. While the intergranular collisions dominate the entire sheet for massive particles, turbulent suspension is more important relative to intergranular interaction for finer particles. Hence, accurate prediction of flow turbulence and particle-turbulence interaction become critical for fine sediment transport. Our numerical experiments suggest that the existing parameterization for the effect of particles on the damping of fluid turbulence in the fluid phase k-ε equation is very sensitive to the resulting sediment transport. Despite these *ad hoc* parameterizations (mostly in ε equation) work reasonably well for dilute flow, modifications are required for more concentrated condition. According to the DNS results for particle-laden isotropic turbulent flow of Squire & Eaton (1994), the enstrophy (a measure for the intensity of instantaneous vorticity) production due to vortex stretching is significantly attenuated for fine particles and the numerical coefficient before the turbulent dissipation term in the ε equation need to be increased. Additionally, strong interplay between turbulent eddy and light particle generates extra vorticity fluctuation, which requires reducing the coefficient before the sediment destruction term in the ε equation. Adopting these DNS evidences into the present *ad hoc* ε equation, the two-phase model is able to simulate concentrated sheet flow transport of medium to fine sand measured by several different laboratory studies (figure 2). In Dohmen-Janssen, Kroekenstoel, Hassan & Ribberink. (2002), sand is driven by combined wave and current flow in a U-tube, the two-phase model predicts very well the time-averaged mean current velocity profile, suggesting that both the nonlinear wave-current interaction in the boundary layer and fluid-sediment interactions in the concentrated sheet flow layer are captured (left panels of figure 2). In O'Donoguhe & Wright (2004), sand is driven by flow velocity of Stokes 2^{nd}-order shape in a U-tube. The two-phase model captures the time evolution of sediment concentration in both the concentrated pick-up layer and more dilute suspension layer (right panels of figure 2). The present two-phase model adopts kinetic theory of collisional granular flow for the closure of particle stresses. Because there has been concern that finer sand is not collisional, several existing rheological model for concentrated viscous suspension (e.g., Bagnold 1954; Nott & Brady 1994) has been adopted to replace the kinetic theory. However, we do not find significant improvement of the model results using different rheology closure because the transport of fine sediment is dominated by turbulent suspension and the parameterization in the ε equation. Motivated by these findings and limitations in the present ensemble-averaged two-phase sheet flow model, we are currently extending the two-phase model into a full 3D multi-phase LES type model for concentrated sediment transport (resolving the mobile bed, no reference concentration is needed). In the present ensemble-averaged formulation, the *ad hoc* ε-equation is inevitable because the turbulent energy cascade and more importantly the turbulence-particle interactions must be modeled at all scales. A full 3D multi-phase formulation will allow directly resolving most of the anisotropic, non-universal, nonlinear interactions to the scale comparable to the grid size and hence significantly improve the model accuracy.

We are currently also developing a simplified multi-phase model for fine sediment, such as fluid mud transport of timescale as long as several tidal cycles. This model adopts closure of sediment stresses based on concentrated viscous suspension and is able to capture typical lutocline and wave-supported gravity-driven turbidity flow observed on the continental shelf (e.g., Trowbridge & Kineke 1994; Traykovski et al. 2000). The future goal is to combine the full two-phase model (for mdeium and coarse sand) and the simplified model (for mud and silt) to develop a multi-phase multi-class (e.g., sand and mud) sediment trasnsport modeling framework.

RANS wave model (COBRAS):

A phase/depth resolving wave hydrodynamic model solving Reynolds-Averaged Navier Stokes equation with k-ε turbulence closure and the volume of fluid numerical scheme for free-surface tracking is utilized as a numerical wave tank to simulate the wave shoaling and breaking processes in the field-scale surf zone. Several minor extensions to the model, including setting up arbitrary beach profile according to beach survey data and sending random wave train using field measured free-surface fluctuation, are implemented into the numerical model. These extensions are crucial in the future to realistically simulate the physical experiment during CROSSTEX. Through collaboration with Dr. Raubenheimer (WHOI), the numerical model is tested with field measured wave hydrodynamics in the surf zone at Torry Pine beach , CA (SwashX, Raubenheimer 2002). In figure 3, a 12-minute long wave train is sent into the numerical wave tank according to the measured free-surface fluctuation at the most offshore location (x=185m). The model is initialized with a quiescent flow field and a beach profile according to detailed CBASS and dolly survey data. The first 4 minute of the simulation is calculated as the warm-up phase to establish a random wave field in the numerical surf zone similar to that in the field. The numerical results of the subsequent 8-minutes are analyzed and compared with the corresponding measured free-surface fluctuations (figure 3). The model predicts reasonably well the R.M.S. variation of wave height (figure 3a) across the surf zone as well as the detailed intra-wave free-surface fluctuations at several different locations (figure 3b). The present numerical resolution (30cm in the cross-shore direction and 2.5 cm in the vertical direction) is sufficient to resolve the cross-shore transformation of breaking waves and hydrodynamics in the surf zone (except the swash zone) within affordable computational time (20 hour computer time for a 12 minute simulation on a Pentium 3.2 GHz PC). Finer resolution can be used to better simulate the swash zone with a higher computational cost. Hence, we conclude that the RANS wave model is able to serve as a useful tool to simulate the detailed physical experiment of CROSSTEX, which is smaller than the SwashX field experiment both in length and depth (The length of the CROSSTEX flume is about 100 meter and the typical duration of wave train is 20 minutes).

IMPACT/APPLICATIONS

One of the greatest challenges in understanding coastal processes is perhaps the interactions of mechanisms that take place at vastly different temporal and spatial scales. Accurate prediction on specific physical problem (e.g., beach profile evolution) may require effective parameterization of processes at smaller scale (e.g., sediment transport in wave boundary layer). The present research efforts focus on developing detailed numerical models for sediment transport and wave hydrodynamics as well as rational parameterizations of these small-scale process. These numerical models and parameterizations will be useful for understanding large-scale coastal processes and further development of predictive tools. The multi-phase approach adopted here is currently extended into a multi-phase modeling framework for the fate of various sediment classes (mud and sand) undergo initial deposition, wave-current resuspension and gravity-driven turbidity flow processes in heterogeneous coastal environment.

RELATED PROJECTS

Through ONR grant (N00014-04-10217), Hsu collaborated with Dr. Elgar (WHOI), Dr. Kirby (University of Delaware) and Dr. Hanes (U. S. Geological Survey) to develop effective parameterization for wave-induced sediment transport using a two-phase model and field data. During year 1, a phase-resolving parameterization was developed for wave-induced sediment transport (Hsu, Elgar & Guza, submitted). This year, this parameterization is further extended for strong wave-current interaction in the boundary layer (Hsu, submitted). Through collaboration with one of the CROSSTEX projects focus on sandbar migration (Dr. Kirby (UD) and Dr. Ozkon-Haller, Dr. Haller at Oregon State University), comprehensive data will be available to test the new parameterizations.

Through NSF Information Technology Research Grant (CTS-0426811), Hsu collaborated with Dr. Raubenheimer (WHOI), Dr. Lynett (Texas A&M University) and Dr. Liu (Cornell University) to develop multi-scale numerical models for coastal prediction and management. Through this collaboration, field data of inner-surf zone measured during SwashX is available and utilized to calibrate the RANS wave model and sediment transport parameterization. Research results obtained from CROSSTEX will also be beneficial to this NSF project.

Hsu and Trowbridge will further calibrate the suspended load formulation, including improved near-bed boundary conditions in the RANS wave model via collaboration with several other CROSSTEX projects focus on measuring suspended sediment under breaking waves (Dr. Cox and Dr. Maddux of Oregon State University) and nonbreaking waves (Dr. Stanton of Naval Postgraduate School and Dr. Foster of Ohio State University). Further developments of the two-phase model are currently conducted via collaboration with Dr. Liu and Dr. Jenkins (Cornell University). Dr. Liu is also the PI of another CROSSTEX project focus on sediment transport in the swash zone. Hsu also currently collaborated with another CROSSTEX participant Dr. Slinn (University of Florida) to develop multi-dimensional model for wave-mud dynamics.

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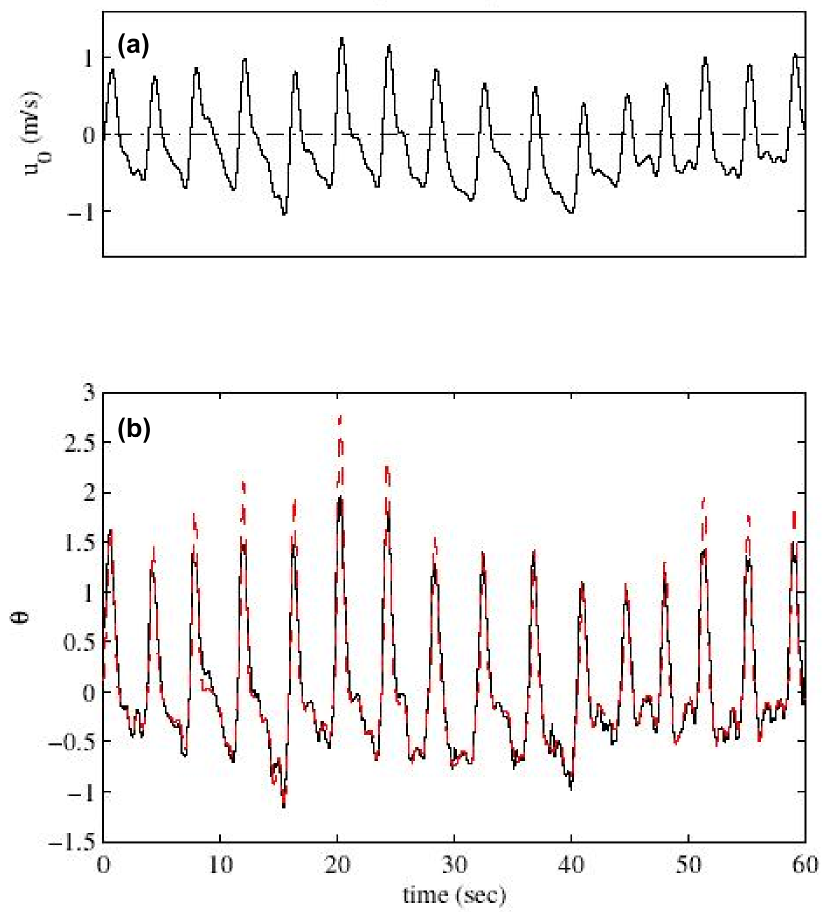

Fig1. Near-bed cross-shore flow velocity time series (a) measured under a random shoaling (broken) wave group near a concrete bar crest (fixed bed) during the CROSSTEX pilot experiment (Scott et al. 2005) is utilized to drive the two-phase sheet flow model. The model predicts (b) the time-dependent nondimensional bottom stress (i.e., Shields parameter, black curve) for mobile sand bed (sand diameter 0.18mm) often exceeds 0.8, a critical value for sheet flow. Time-dependent bottom stress estimated from computationally efficient single-phase boundary layer model with k-ε turbulence closure (red-dashed curve) is well correlated (square correlation 0.9) to that calculated by the two-phase model (black curve) provided that an elevated roughness height Ks=5d is used. When predicting beach profile change over much longer time-scale (days to weeks), the single-phase boundary layer model (with elevated roughness) may be an effective approach to calculate sediment transport rate (Hsu & Raubenheimer, accepted; Hsu, Elgar & Guza, submitted).

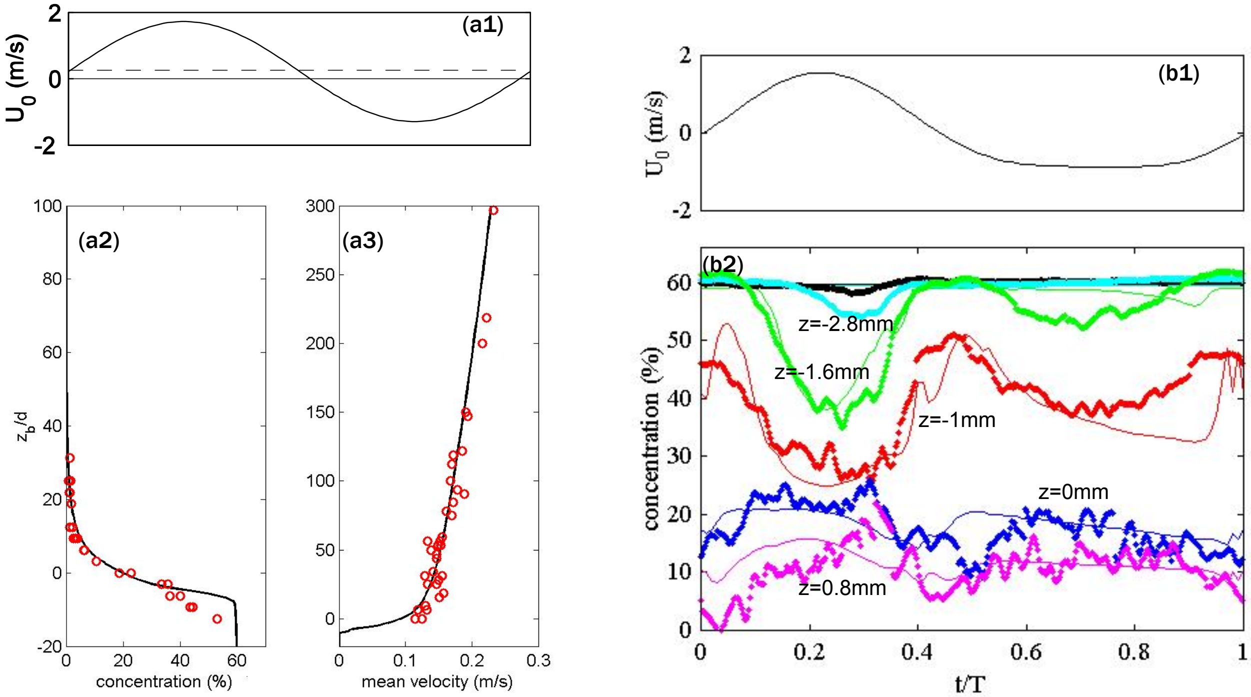

Fig2. Comparisons between the two-phase model results (curve) and data measured in U-tube experiments (symbols). Left panels (Dohmen-Janssen et al. 2002): Sand (d=0.32mm) transport driven by a combined wave-current forcing (a1) of sinusoidal oscillatory velocity (amplitude 1.47m/s , period 7.2 sec) plus a mean current (0.26m/s at 10 cm above the bed). The model predicts satisfactory time-averaged concentration (a2) and velocity (a3) profiles within the wave-current boundary layer and the sheet flow layer. Right Panel (O'Donoghue & Wright 2004): Sand (d=0.27mm) transport driven by flow velocity of Stokes' 2nd-order wave shape with R.M.S. velocity 1.0 m/s and period 6.5 sec (b1). The model predict reasonably well the time-dependent sediment concentration in the suspension layer (z>0mm) and pick-up layer (z<0mm). U-tube data obtained in collaboration with Marjolein Dohmen-Janssen and Tom O'Donoghue

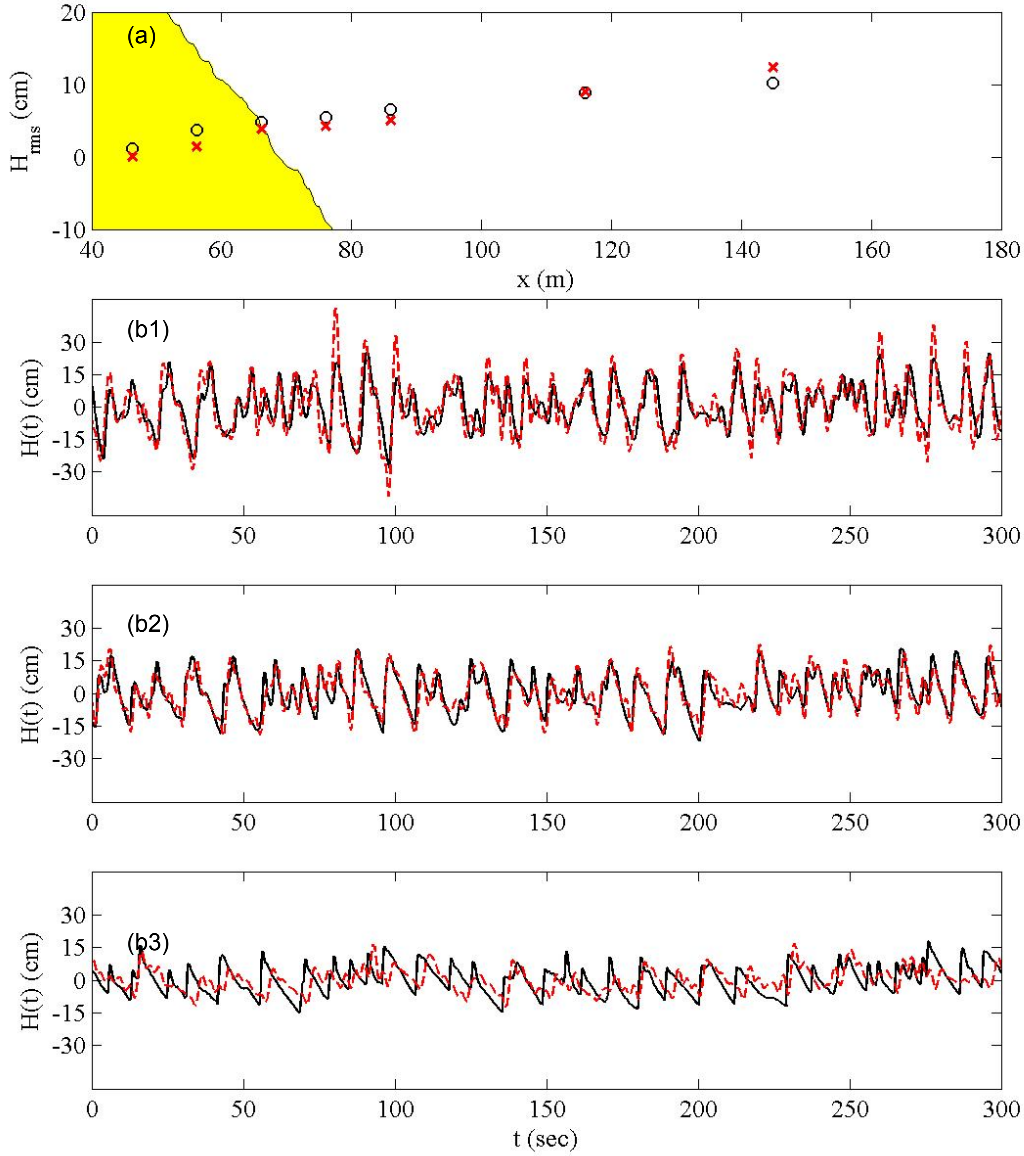

Fig3. Wave shoaling across the surf zone simulated by the RANS wave model. Field measured free-surface elevation time series (8 minute with only 5 minute shown) during SwashX experiment at x=185m is used to drive the numerical wave model. The numerical model predict cross-shore variation of R.M.S wave height (circle in (a)) within the surf zone agrees well with the measured data (crosses in (a)). Detailed intra-wave time series of wave height in the outer surf zone (b1) and (b2) (x=145m and 116m) are well captured by the numerical model (solid curves) when compared with measured data (dashed curves). In the inner surf zone, the evolution of wave height (b3, x=86m) is also captured by the numerical model. Flow in the swash zone is not well-resolved for the present grid resolution.